

# **Reducing Diesel Particulate Emissions by > 99 %**

**Approach and Field Experience  
in Switzerland**

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## Subjects for Discussion

- Retrofit Strategy and Procedures
- Swiss Experience with Diesel Particulate traps offroad and onroad
- Filter-Specification and Filter-Verification Procedures
- Particle Definition and UF-Particle Metrology

## The Swiss Chronicle to reduce Diesel Particulate emissions by > 99 %

- Offroad Emissions Inventory 1993  
(computer-model for predictions now available on CD)
- **VERT-Project 1994-1998** to define and prove BAT
- BUWAL (Swiss EPA):  
Clean Air Act Amendments 1998
  - **Diesel Particulate classified as carcinogenic**  
(to be minimized acc. to BAT irrespective of cost)
  - PM 10 – Limit 20 g/m<sup>3</sup> (exceeded in all cities)
  - Traps for construction sites in/nearby cities
- SUVA (Swiss Occupational Health authority):  
**Traps mandatory** for the working place 3/2000
- Implementation Tools:
  - Trap-System Specification 1996
  - Trap-System-Certification Procedure 1997
  - Filter-List of all certified traps on the Net 1998
  - Ultrafine Particle Metrology “NanoMet” 1999
  - EC-oriented Calibration method by EAM 1999
  - Trap OBD-Systems “LogLink” 1999
  - Trap Manufacturer Association AKPF 1998
  - Nanoparticle Measurement Conference since 1997
- **> 3000 traps in operation** – controlled by field testing  
(should be 100 % yearly control – now only 15 %)
- STUMP-Postulat: “**Retrofit of all swiss HDV-onroad (66'000)**  
with efficient particulate filters as soon as possible”

## Health Effect of Diesel Particles in Switzerland

- PM10-limit ( $20 \mu\text{g}/\text{m}^3$ ) is exceeded in all agglomerations of to 3 times
- Diesel soot up to 50% of PM10 in cities
- Swiss epidemiological study SCARPOL shows  
> 30% increase of lung deceases when doubling PM10 with children
- 2100 premature death (population 6 Mio)
- 4.4% increase of mortality with  $10 \mu\text{g}/\text{m}^3$  increase of PM10
- 426'000 days out of work
- 1600 Mio SFr. total cost
- Carcinogenicity of Diesel soot stands for about 60% of all toxic substances in the air
- 90% of all occupational health cases are due to lung invading toxic substances

## Swiss Offroad Emission Inventory

- Diesel-Inventory based on ca 300 engine maps 1994  
Published 1996, BUWAL Reports 23 and 49
- Offroad Diesels emit as much PM as onroad Diesels  
Share deteriorates as onroad Diesels become cleaner by regulation and offroad not
- Offroad Diesel emission is serious local pollution  
Critical situation for construction sites in cities
- Legal Situation: Switzerland can act offroad  
whereas it is preempted from actions onroad for new vehicles because of EU-contracts
- Review of offroad inventory 1998 shows no improvement
- Computer model established to predict emissions for given local situations like construction sites  
available on CD
- Clean Air Act LRV modified accordingly 1998

## VERT-Project 1994 - 1998

(including 2 years field test with the construction machines)

- Joint European Project of Occupational Health Authorities CH/D/A and swiss Clean Air Authority BUWAL with innovative industrial partners
- Target 1: **establish BAT (Best Available Technology)** to reduce Diesel Particulate-Emissions to  $< 1 \%$  with respect to solid insoluble (soot) particles acc. to swiss definition applicable to all existing diesels using market available technology within 3 years
- Target 2: evaluate or develop certification procedures and field controls for the retrofit-technology
- Target 3: establish implementation tools
- **Particulate - (Particle-) Definition:**
  - Solid particles: soot EC-core + adsorbed OC
  - Size range 10 – 500 nm
- **Results:**
  - Modern Diesels reduce PM but not particle number emission
  - Clean Fuels do reduce PM but not particle number emission
  - Oxi-Catalysts do not reduce particle number emission but increase NO<sub>2</sub> and SO<sub>3</sub> to unacceptable levels
  - Traps reduce particle numbers by  $> 95 \%$  (up to 99%)
  - Traps do not loose efficiency after 2000 hrs field test
- **Specifications and test procedures** developed with industrial partners accepted by Occ. Health Authorities of Switzerland, Germany, Austria, Canada (DEEP) and US (NIOSH) Swiss Clean Air Authority BUWAL and German UBA

## VERT-Findings and Conclusions

- Engines
  - new engines emit less PM (Particulate Mass) but as many solid particles as older engines and particle size tends to be smaller
  - small engines emit more particles
  - new engines are more sensitive to back pressure -TC
  - new engines are more difficult to retrofit -lower temp.
  - ⇒ all engines must be retrofitted
- Fuel with low S
  - no direct impact on soot particle number reduction
  - red. of sulfuric acid aerosols and sulfate particles
  - easier to retrofit with low S (more technologies)
  - ⇒ S should be < 10 ppm
- Fuel Additives
  - additives form additional particles (heavy metals!)
  - additives can be aggressive to filter materials
  - additives can form deposits on injection nozzles
- Lubrication Oil
  - ash particles tend to clog filters
  - ⇒ low ash, low TBN
  - ⇒ running-in concept
  - ⇒ oil consumption <1 % fuel cons. (new eng. 0,15 %)
- Oxidants:
  - HC, CO - conversion has little importance
  - $\text{SO}_2 \rightarrow \text{SO}_3$  conversion problematic
  - $\text{NO} \rightarrow \text{NO}_2$  conversion unacceptable
  - ⇒ Oxidant can not be permitted for some applications
- Traps
  - filtration efficiency > 99% (soot) - many systems
  - no pronounced aging effects
  - secondary emissions avoidable
  - standard noise attenuation
  - regeneration can be problematic
  - ⇒ careful application-oriented trap selection
  - ⇒ more active regeneration system elements
  - ⇒ improved on board controls
- Field controls
  - instrumentation available for black smoke and gaseous emission measurement
  - test cycle at site: free acc, + high/low idle
  - ⇒ 100% control once per year

## Definition of Diesel Particulate or Diesel-emitted Particles ?

- **Definition with respect to Health Effect**  
Mass ? Count ? Surface ? Size (aerodynamic or mobility ?)
- **Definition regarding chemical substance**  
Or at least “key substance”
- **Definition regarding physical appearance**  
phase, size parameters
- **Definition regarding sampling spot**  
tailpipe ? engine ? anywhere ??
- **Definition regarding sampling conditions**  
Load, speed, cycle, steady state/transient ?

**Swiss Definition:** Solid Particles  
and anything adsorbed to it  
at tail-pipe conditions  
in the size range 10-500 nm

**Dreams:**

- Definition and Metrology should be worldwide identical for engine emission and ambient meas.
- EC should be used as key substance

## Swiss Legislation / Regulations 2001

"Diesel soot particles are carcinogenic and must therefore be minimized acc. to BAT"

- BUWAL (Swiss Environnement Protection Agency)  
requires **traps for Diesel at construction sites**  
In or closeby cities  
Implementation by local government (Cantons)  
only VERT-certified trap-systems recommended  
periodic field control required (yearly)  
exceptions for very short operation period (weeks)  
in force 1998  
<http://www.buwal.ch/projekte/luft/partikelfilter/e/index.htm>
- SUVA (Swiss Occupational Health Authority)  
requires traps for underground work  
and all closed or semi-closed rooms  
**100 % application, no exceptions**  
only VERT-certified traps are accepted  
in force 2000  
<http://www.suva.ch>
- Trap systems must comply with other legislation  
(noise, safety)  
in force 1990/95
- Trap systems using catalytic coatings or fuel catalysts  
**must prove "no emission of secondary toxic emissions"**  
**In force 1990**

## Motivation Tools to use Traps in nonregulated applications

- LSVA-Tax, depending on emission level, load and mileage and location (only when inside swiss borders detected by GPS-Sensors)
- Publication on Diesel health risks on all levels
- Direct mailing to relevant groups (truckers, construction, public transport)
- Remind managers on their legal responsibility to minimize health risk ( carcinogenic ! ) for employees (Obligationen-Recht OR since 1913)
- Instruction on all educational levels (mechanics to university students)
- Green stickers for clean retrofitted vehicles
- Field tests to prove emission quality paid by government
- Consultancy services on how to select and use traps available to anybody at no cost (government-paid)
- Updated "white lists" published on successful retrofit actions
- "Black list" of those industrial partners who slow down emission reduction process (under preparation)

## Trap-System Specification

- Filtration rate for Particulate Mass      desirable > 80 %
- Filtration rate for Particle Number      mandatory > 95 %
- Filtration rate for EC-Mass      mandatory > 90 %  
 For the fresh, loaded and regenerated trap  
 the new and old trap (old = 2000 hrs of field operation)  
 also transient during regeneration
- No increase of any other toxic emissions  
 CO, HC, NO, NO<sub>2</sub>, N<sub>2</sub>O  
 Sulfates (desirable)  
 PAH, Nitro-PAH, PCDD/F  
 Heavy metals in any form
- Pressure loss for loaded trap < 200 mbar  
 New traps should unloaded be below 50
- Automatic dosing systems for fuel additives
- Electronic OBC with 2 alarm levels for  
 trap clogging (2 stages orange/red) and trap damage
- Field refuse criterion: < 10 % opacity (future 5 %)  
 Equivalent 0,24 1/m and 0,033 g/m<sup>3</sup>  
 during snap acceleration (low to high idle)
- Cost < 100 SFr./kW (future < 50 SFr/kW)
- Noise, Safety, Size, Heat radiation
- Investment, maintenance cost, Service Interval
- + + + + + see Filter List

## Trap Suitability Test Concept

### VFT = VERT Filter Test

Stage 1: bench test with new filter

Stage 2: field test > 2000 field operation hours

Stage 3: bench test with field tested filter

All system components (additive dosing system, OBD ) must be included in the test procedure

### VSET = VERT Secondary Emission Test

must be performed with all systems

with build-in catalytic activity (Swiss law since 1990)

PAH; Nitro-PAH; PCDD/F; NO<sub>2</sub>; N<sub>2</sub>O, Aldehydes ....

### VFT<sub>K</sub> = shortened VFT

for systems which have successfully passed VFT after minor technical modifications

### Additional Conditions for Regeneration Additives

- New substances must be registered depending on general toxicity criteria
- Filter + Additive must have successfully passed VFT
- Filter + Additive must have successfully passed VSET
- Automatic on-board dosing system or equivalent technique
- OBD with Dosing-Stop if filter leaks
- Environmentally friendly system to clean filter from additive-, fuel- and lubeoil-ashes

## VERT Filter- Control Philosophy

### Basic Assumptions (based on deep bed filter theory)

- Trapping efficiency can only be defined for solid particles
- Trapping efficiency depends mainly on particle size, space velocity and temperature
- Trapping efficiency is equal for steady state and transient

### Conclusions for Particle Definition

- Particle size and phase (solid/liquid) must be defined otherwise no proper evaluation is possible

### Conclusion for the Measurement

- Sampling and Sensors must be able to separate solid and volatile particles and analyse penetration size-classified.

### Conclusions for the Type Approval Concept

- Verification of a filter-system (family test) is sufficient on one representative Diesel engine (or even on a filter test machine) at max. space velocity acc. to VFT+VSET
- Resulting efficiency will be valid for any other application
- The combination Engine + Filter must not be verified

### Conclusions for the Filter-System Definition

- Filter-System production specifications must be well defined and printed on the filter label incl. manufacture date etc.

### Conclusions for Field Control

- 100 % individual field control (yearly) is necessary
- Opacimetry sufficient for now (future more sensitive method)

## Retrofit-Philosophy for Demonstration Fleets

“highest possible efficiency and reliability  
to build up confidence ”

### Procedure for successful retrofitting

- engine-out emission measurement before retrofitting
- proper filter selection process (see sep.slide)
- only filter systems with long term field experience
- only systems including electronic OBC and alarms
- only active regeneration systems
- low-Sulfur fuel ( < 10 ppm)
- Lube-Oil: low ash (<0,5), low Sulfur (<0,2), low TBN (<5)
- Emission test immediately after retrofit (gases + opacity)  
and repeated every 3 month  
to be performed by filter manufacturer and control auth.
- 1 out of 10 filters should bench tested before and after test  
period including particle size penetration and sec.emiss.
- close control and evaluation of continuously monitored  
back pressure and temperature data
- regular driver interviews
- engine out emission measurement after demonstration  
phase

## Proposed Retrofit Technology for captive Fleets

- Ceramic wall flow filters – Cordierite or SiC
- Electric regeneration onboard / standstill “plug-in type” combined with
- Catalytic fuel additives with automatic dosing  
this combination makes a lot of sense:
  - raw emission reduction up to 30 %
  - part-regeneration during operation
  - low temperature regeneration (less energy, less time )
  - small filter size
- Onboard Filter-Electronics include regeneration control
- Garage-Infrastructure:
  - access to electricity for each vehicle
  - air supply
  - ventilation and ventilation control
- Systems available by
  - JMS/D using the OCTEL-Fe-additive
  - LUBRIZOL/UNICAT using the CDT Ce/Fe-additive
  - IBIDEN/? using the RHODIA-additive
- Field Experience with O/S-Regeneration  
in Switzerland > 650 units, in use since 10 years  
worldwide > 10'000 units
- Field Experience with combination O/S-Reg.&Additive  
130 Systems / one manufacturer  
in operation since 4 years - no breakdowns reported

### This Retrofit-system

- guarantees highest filtration efficiency under all conditions
- is applicable to any engine and operation cycle
- is proven, assures high reliability and long life
- is readily available at high cost-effectiveness

## Which Engines should be retrofitted and why

- Small engines emit specifically (g/kWh) more Particles
- The product Power (kW) X Emission Factor (g/kWh) is close to constant
- It would therefore be wrong to not retrofit small engines
- Small engines work closer to people
- all Diesel engines should be retrofitted  
... except

## Which Engines should not be retrofitted and why

- 2-stroke engines since they emit too much lubeoil and are very backpressure-sensitive
- Any engine consuming more than 2% (1% ?) lubeOil compared to fuel consumption
- Excessive smokers: Bosch > 5 / Opacity > 80 %

What to do with such engines: rebuild or scrap !

Swiss BauRLL: Diesel engines, which can not be retrofitted with particulate traps for some technical or other reasons are no longer allowed to be operated

## Risks for Filters

- Filter overheating during regeneration
- Filter fracture due to vibrations
- Filter material damage due to oil ash compounds
- Filter clogging due to silencer fibers
- Filter overloading with following fracture or blow off

## Regeneration Malfunctions

- Operation temperature too low or peaks too short
- Additive dosing inadequate
- Engine deterioration (injection nozzle failure)

## Risk for the Engine

- Excessive backpressure  
Increases fuel consumption and material temperature
- No engine damage known due to particulate trap application
- Additive suppliers warranty in case of engine damage

## Risks for the environment and people

- High exhaust emission temperature during regenerations

## Measures to minimize such risks

- Electronic on-board control with 2 alarm levels
- Automatic on board additive dosing
- Active systems whenever operation temperatures very too much and low level operation is not excluded
- Permit only systems which have passed 2000 hrs-Test
- Assure proper trap selection with preceeding data-logging
- Periodic emission control once per year
- Exclude high-emitters
- Use cleaner fuels and lubeoils

## Engine/Vehicle-Warranty Constraints

Every Engine Manufacturer will decline the warranty and stop to feel responsible for the proper function of the engine if a Diesel Particulate Trap is retrofitted

We may be able to overcome this  
by clearly defining the interface conditions:

1. by setting a max. value for backpressure : 200 mbar
2. by monitoring this value with memory functions
3. by avoiding vehicle chassis modifications
4. by building traps within the space used by the muffler

## Test-Protocol for VERT Filter Test VFT

### Procedure:

- ISO 8178/4 C1: 4 operation points steady state
- transient: snap on test (free acceleration)
- base line without filter / standard fuel
- filter conditions: fresh, loaded and regenerated
- with/without regenerating additive
- transient monitoring during regeneration for all emission components incl. particles
- complete test new and after 2000 hrs

### Instrumentation:

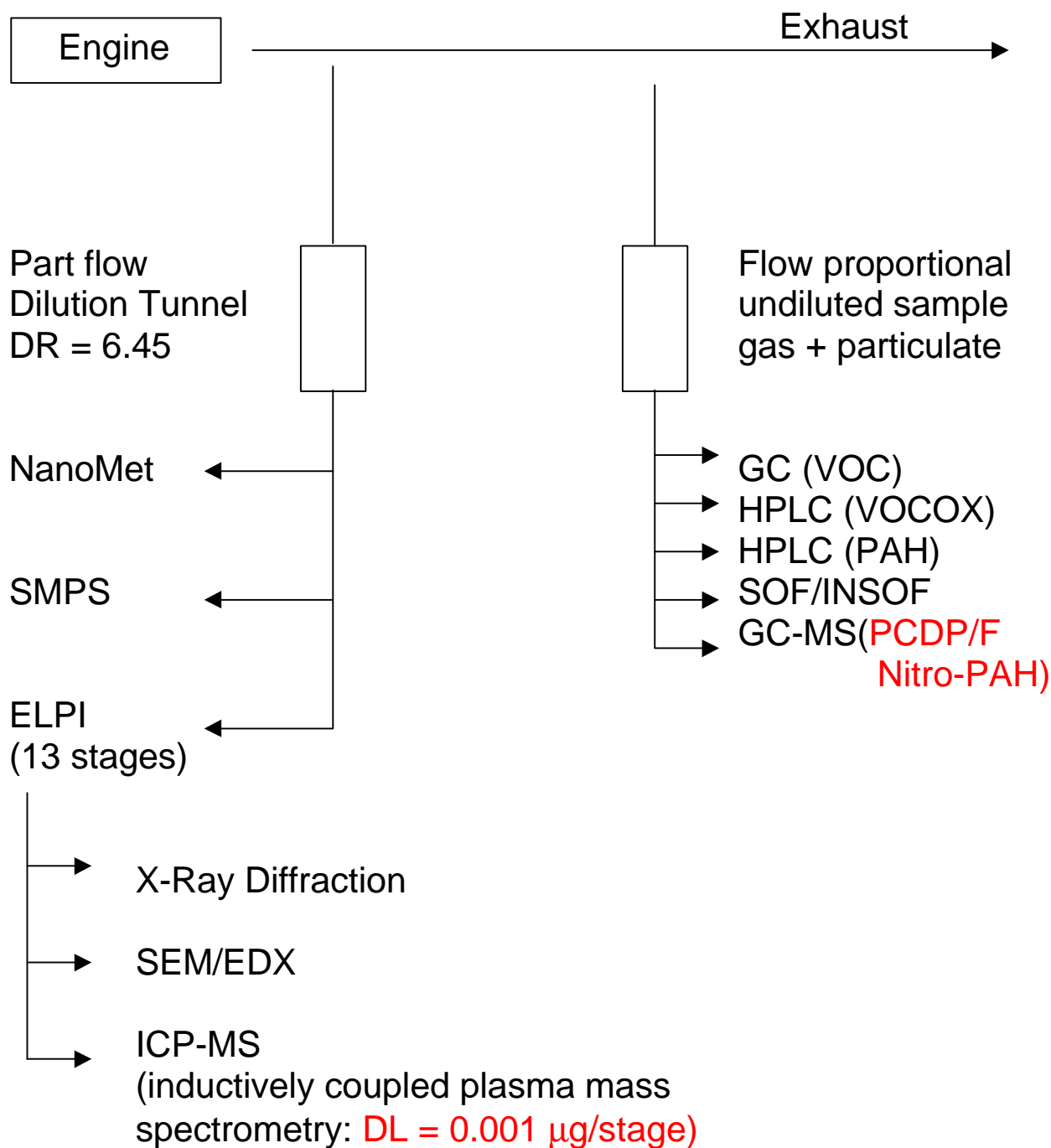
- Standard emission instrumentation for PM, NO/NO<sub>2</sub>, HC, CO
- Particle number concentration and size analysis : SMPS, ELPI, NanoMet, CPC
- chem. « fingerprint »: PAS, DC
- Coulometry for EC

### Conditions:

- Fuel: < 50 ppm S or as require
- LubeOil: low ash, low S, TBN < 5

## Test-Protocol for VSET

Sampling during 2-4 hrs of repeated ISO 8178 test cycles



## Filter-List

- Lists all trap-systems which have successfully passed VERT Filter Test VFT and VERT-Secondary Emissions Test VSET
- Now 19 systems on the list
- Updated every 6 month – actual list 1.April 2001
- on BUWAL and SUVA-Homepages and DieselNet
- A system will be put on the list after VFT Stage 1  
If retest after 2000 hrs field is not successful  
or not performed after latest 2 years  
the trap system will be taken off the list
- Retesting becomes mandatory if 10 % (next step 5%) of reported field controls are exceeding 0,24 1/m during snap on test
- The List is widely accepted by manufacturers and users and has become the most important implementation tool

## Application Oriented Trap Selection for Retrofits (1)

- Datalogging:  $T_{\text{exh.}}$  / RPM / P
    - Evaluation of Temperature availability
    - Evaluation of Temp-Episode-Statistics
    - Evaluation of repeatability
  - Test raw emission
  - Test lube oil consumption
  - Exclude old engines with exorbitant emissions and oil consumpt.
  - Logistics for Standstill Regeneration available?
  - Logistics for exchange-trap available?
- ↳ Select appropriate trap/regeneration-system
- active offline
  - active online standstill
  - full flow burner
  - passive additive assisted
  - passive catalyst assisted
  - combinations
- ↳ never install trap system without data-logging before and without control system with 2 alarm levels
- ↳ Never forget to check efficiency and back pressure build up after installation

## Field control of Trap-Systems

### Actual Use:      **mobile Opacimeter**

not very sensitive for low PM-emissions  
insensitive for UF-particles  
influenced by some non PM-products  
**but good enough to identify trap damage**  
widely available in Switzerland  
because of valid onroad legislation

However **Opacimetry does not monitor ultrafine particulate** emission and will not be sufficiently sensitive for future engines

### Future :      **NanoMet**

Identifies trap efficiency by simultaneous transient measurement upstream and downstream during snap-on acceleration and  
can monitor ambient effect (threshold control) with the same instrument

## Trap-Retrofit Statistics and Field Results/Overview

- **2383 Traps in use in Switzerland (October 2000)**

- 78 on trucks
- 689 on buses
- 800 on construction machines
- 589 on fork lifts
- 81 on stationary engines
- 118 on rail and ships
- 28 for periodic use (garages)

It is expected that this numbers will double in 2001/2

- **Failures:**

- 154 reported failures over 10 years: 6.5%
- 84 reported failures after 1995 : 3.5%
- 56 experimental field test systems:

→ Failure rate net: 2.6%

may be somewhat higher (5% ?)

Target is < 1 %

- **Emission Measurements in the Field in 2000**

- 207 measurements
- Complains (exceeding 0,24 1/m Opacity) : 37 total
- excluding unsuccessful experimental system: 7

→ Complains net: 3.3%

## Filter-Systems in use in Switzerland (October 2000)

	Number	Application	Since
<b>DB/M &amp; H</b> 3M Fiber Candle Filter, Cu/Additive Regeneration	237	City bus	1990
<b>UNIKAT/ECS</b> Cordierith/SiC Wall Flow, Offline electrical heating	391	Truck, Offroad	1990
<b>DEUTZ</b> Cordierith Wall Flow, Full Flow Burner	131	Offroad	1992
<b>GfA</b> Cordierith Wall Flow, Additive assisted	210	Forklift	1993
<b>HUG</b> Fiber Filter, Full Flow Burner	49	Ship, Rail	1994
<b>HUSS</b> SiC Wall Flow, Offline electrical heating	160	Offroad	1994
<b>HJS</b> Sinter Metal Wall Flow, Additive assisted	10	Offroad	1996
<b>JOHNSON MATTHEY</b> SiC Wall Flow, Additive assisted, Offline electrical heating	181	Offroad	1996
<b>HJS/EMINOX</b> Cordierith Wall Flow, CRT	650	Offroad, City bus	1997
<b>OBERLAND</b> Knitted Ceramic Fiber Candle Additive Assisted	291	Bus, Truck, Offroad	1997
<b>AMMANN</b> Knitted Fiber, Additive assisted	19	Construction	1998
<b>EHC</b> Snap on glass fiber	28	Bus, Truck	1999
<b>ENGELHARD</b> Cordierith Wall Flow, Catalytical coating	< 10	Bus	2000
<b>INTECO</b> Metal Fiber Fleece. Catalyt Coating	10	Offroad	2000
<b>DCL</b> SiC Wall Flow, Additive assisted	10	Offroad	2000

## FIELD- EXPERIENCE

### Statistics

	Application	Reported Failures
Passenger Car	-	-
Truck	78	6
City Bus	689	52
Coaches	-	-
Construction	800	50
Fork Lift	589	35
Ship / Rail	118	5
Stationary	81	6
Snap on	28	-

### Efficiencies for 8 qualified systems

System	1	99.8%
	2	99,6%
	3	99,4%
	4	99,4%
	5	99,3%
	6	98.1%
	7	96.9%
	8	96.7%

### Operation Times

Fahrzeugtyp	Filter Type	Operation	
City Bus	DB/ M&H	> 750'000 km	VBZ Zürich
Truck	UNIKAT	> 500'000 km	KIBAG Zürich
Construction	UNIKAT	> 10'000 op.hrs	Dübendorfer
Fork Lift	HUSS	> 20'000 op.hrs	Landor AG
Ship	HUG	> 10'000 op.hrs	Lake of Konstanz
Stationary	BUCK	> 10'000 op.hrs	Reichstag Berlin

## Filter-System Specific Problems

Filter Systems	Fail.Rate	Failure Type	Reasons	Measure
UNIKAT	low	Overload	too small	increase capacity
DEUTZ	low	fracture/melting	inappropriate control	adjust algorithm
HJS/CRT	middle	overload/fracture	Temp. low; NO <sub>2</sub> /soot low	change regen. <sup>1)</sup>
JMC	middle	overload/fracture	Temp. low	change regen.
OBERLAND	high	overload/blow off	Temp. low, Dosing inapt	Improve filter and dosing system
HUSS	low	Overload	too small	increase capacity
GfA	high	overload/fracture	Temp. low	change regen. type
DB/M + H	high	overload/candle damage	uncontrolled regeneration	repare
all	middle	ash loading	high ash lubrication oils	new lube oils

<sup>1)</sup> Change from passive to active regeneration

## The Trap Manufacturer Association AKPF

A working group of actually 20 trap/trap-system-manufacturers

(D, S, A, F, NL, UK, CH, USA, CAN )

with the following activities:

- Prepare technical standards
- Analyse Field experience
- Dialog with Authorities
- User-Information
- Define research topics
- Support new metrology

AKPF has become a very important dialog-partner for the Swiss authorities.

Meetings every 6 month

Information is public

Open to any company beeing active in the field

Homepage: [www.akpf.org/](http://www.akpf.org/)

## How to measure engine emitted Aerosols

- **Health effect oriented**: Combine characterization of mass, surface, number, chemical composition
- **Transient** : time constant 1 sec to monitor emission peaks during ETC
- **Sensitive**: better than 0,5 g/m<sup>3</sup> EC to use same method for emission and ambient
- **Robust** : to use same method for certification and field control
- **EC-oriented for traceability**
- **At Tail-Pipe-conditions**: avoiding all condensation artefacts by high/hot dilution (D >1:100 / >150°C)

No satisfying method was available in 1995  
BUWAL therefore supported development  
of a new Aerosol-Characterization method  
“NanoMet” (University-research spin off)

- High/hot dilution
- Mobility sizing
- Double-sensor technology PAS+DC

Instrument is now commercially available by Matter Engineering, ([nanomet@matter-engineering.com](mailto:nanomet@matter-engineering.com)) and has just successfully passed round robin test of German Occupational Health Authority

## How to calibrate particle measuring instruments

with respect to a chemical key substance  
and traceability

- METAS (Swiss Office for Measurement) identified “Combustion Aerosol Metrology” as the most important metrology target in 1995
- METAS started consequently to **develop an Combustion Aerosol Standard** to be used for official calibration of any instruments offered by manufacturers
- **CAST (Combustion Aerosol Standard)** is now available by Matter Engineering/Wohlen
- Principle: perfectly controlled diffusion flame combustion
- Composition of particles is > 98 % EC
- Size of Particles 20 – 500 nm on demand
- Concentration can be adjusted by dilution  
3 orders of magnitude variation

## Nanoparticle-Measurement-Conference

yearly since 1997 at Zürich

- **Worldwide participation : 160 participants in 2000**
- **53 Papers and 3 Workshops 2000**
- **3-day-meeting**
- **Proceedings available on CD**
- **No Conference Fee**
- **Next conference: 6/7 August 2001**
- **Call for papers May 31.**  
**Registration: TTM/A. Mayer, CH-5443 Niederrohrdorf**

The NMC is actually the only worldwide meeting of the Nanoparticle Measurement Community in Science and Engineering strictly oriented to characterization of combustion aerosols

## Available Documentations on CD's

- VFT (VERT Filter Test),  
Full Report (IBIDEN)
- VSET (VERT Secondary Emission Test),  
Full Report (CDT)
- BUWAL/SUVA-Filter List
- BUWAL Report 130:  
Retrofit on Swiss HDV of large vehicle fleets
  
- 4 CDs on VERT-Results
- 2 CDs ETH Conferences 1997/98/99/2000
- 1 CD Particle Lexicon
- 1 CD Computer Model Offroad Engines
- 1 CD LogLink Technology
- 1 CD NanoMet + CAST

Further Documentation on Swiss Activities please contact:

- TTM        TTM.a.mayer@bluewin
- BUWAL    docu@buwal.admin.ch
- Suva    Zentraler.Kundendienst@suva.ch

## Particulate Trap Retrofit for all swiss HDV

### “Postulat STUMP”

Request on parliament level Mai 1999  
Accepted by the Swiss government August 1999  
Study on Feasibility concluded August 2000  
Decision expected in fall 2001

- **66'000 HDV onroad**
- **Trap Retrofit justified**  
for new (EURO 2) and up to 20 years old vehicles
- **Cost per vehicle of 5'000 – 12'000 SFR**  
Financing model by emission dependent road tax  
LSVA in force 1.Jan 2001
- **Pilot-Series (12 x 100) starting in 2002 proposed**
- **Technical Feasibility investigated**  
based on in-service statistical analysis of operational  
behaviour for 12 Vehicle classes  
(see BUWAL report 130 and SAE Paper 2001-01-0187)
- **Report on Feasibility available on CD**

## CONCLUSIONS

- Particulate Traps are the only devices readily available to reduce solid combustion particle emission to the requested minimum level
- Trapping efficiency can be as high as 99,9 %
- Reliable Trap systems are available
- Retrofitting traps is possible for all HDV with very few exceptions
- Fuel Sulfur Level should be as low as possible < 10 ppm
- Lubrication Oil:  
ash content and TBN should be low
- Lubrication Oil consumption: < 1% fuel consumption
- Electronic OBD is a must
- Systems must operate fully automatic
- Systems can be designed to avoid all secondary emissions
- Frequent field control is recommended
- Verification procedure must base on submicron solid particle number concentration and particle chemistry

# More Information to Particle Measurement

## Possible Improvements of the gravimetric Method

- **Suppressing dew point effects**  
Sampling temperature > 100 °C
- **Increasing dilution ratio**  
Coming closer to real word conditions
- **Avoid re-entrainment confounding**  
By use of 1 $\mu$ -cyclon
- **Avoid confounding by fuel and oil-effects**  
Use clean substances for certification

## Remaining deficiencies

- no Substance-specific information
- no Aerosol-specific information
- no information on transient effects
- insufficient sensitivity
- no agreement with ambient measurement
- calibration doubtful (just mass but which )

## Basic principles of Measurement

### 1. No change of Mass, Phase and Composition between taking an sample and measuring its properties

any change during measurement process is artefact  
if artefact happens the measurement is not valid

### 2. Object to be measured must be defined

Definitions of mixed substances like

$\text{SO}_x = \text{SO}_2 + \text{SO}_3$ ,

$\text{NO}_x = \text{NO} + \text{NO}_2 + \text{N}_2\text{O}$

$\text{CO}_x = \text{CO} + \text{CO}_2$

$\text{PM} = \text{Soot} + \text{Ash} + \text{Sulfates} + \text{Water} + \text{Engine Wear}$

can not properly be handled and lead to useless information

### 3. Sample Conditions must be defined

Sampling in the engine, before TC, after TC

at the tailpipe, in the dilution tunnel, at road side ???

give different results

Standardization is needed !

### 4. Properties to be measured must be defined

PM or EC or TC or .....

Cumulative mass or size specific

Mass or Surface or Number or .....?

Aerodynamic Diameter or mobility Diameter ?

Substance of which the properties should be measured.

### 5. Accuracy target must be defined

### 6. Calibration must be possible

### 7. Traceability should (must ?) be possible

If we have no agreement on these basic principles  
we better stop talking about measurement of  
Diesel Particulate Emission

## Deficiencies of Legislated Gravimetric Particulate Matter Measurement Procedure

“anything downstream of an engine in an exhaust gas/air-mixture found at 52 °C on a filter paper at undefined humidity and undefined dilution”

- **Does not mimic real world conditions**

Insufficient dilution

Dew point effects not excluded

- **Modifies and falsifies the substance**

Formation of condensates and artefacts

- **No Substance-specific information**

Toxic substances and water have equal value

( 1 single water-droplet and 1 million lung penetrating PAH-coated solid soot particles are equivalent)

- **No Aerosol-specific information**

No information on Particulate Size

Underestimates particle number/surface effects

- **Physical Principal different from ambient Measurement**

No agreement with basic measurement principles

## Targets for new Diesel Particulate Measurement Technology

- **Health oriented information**  
Mass ? Number ? Surface ? Size ? Substance?
- **Size-Specific information**  
according to particle mobility  
size the range 10-1000 nm
- **Substance-specific information**  
differentiate between solid particles  
(carbon and ash) and condensates
- **Sensitivity better then 1 g/m<sup>3</sup>**
- **Time resolution 1 sec**
- **Physical principle identical for  
Emission (certification and in use compliance)  
and Immission (ambient)**
- **Traceability to EC**
  - Repeatability
  - Cost
  - Size
  - Handling

## Alternative methods / New Metrology Candidates

- **SMPS:** count  
mobility sizing + CNC
- **ELPI:** mass  
13 stages impaction
- **NanoMet:** count, surface, substance online  
mobility sizing + double sensing
- **Aethalometry**  
BC equivalent to EC-mass
- **Coulometry**  
EC + OC
- **Laser Induced Incandescence (TIRE-LII)**  
EC primary particles
- **Multi-Wavelength Laser**
- **Light Scattering -Methods**
- **Quartz-Microbalance (TEOM)**
- **Mini-Moudi and other new impactors**
- **SEM and other picture-analysis methods**

## Strange Findings when measuring Diesel Particles

- Where mass is high, number is negligible  
Where number is high, mass is negligible
- Mass downstream trap > mass upstream trap
- Number downstream trap > number upstream trap
- Number changes fast depending on dilution
- Bimodal Size distributions with different substances
- Sensitivity to dilution and sampling temperature
- Artefacts due to sampling conditions
- Reduction of particulate mass but not count

# GRPE / PMP

## Particle Measurement Programme

### Swiss Contributions

- Literature Study on Health-Effects, Measurement and Filtration of UF-solid Particles - 4/01
- **Experimental Study on new Measurement Methods for Type Approval of Diesel Vehicles/ Phase 1 - 5/01**
- Experimental Study Phase 2 – 11/01
- Selecting of promising Metrology Candidates – 12/01
- Testing and Validation - 6/02
- Characterization of advanced Technology - 9/02
- Testing Type Approval Process with adv. Techn. 3/03

Reports prepared for

**FEDRO** Swiss Federal Roads Authority

**FOEFL** Federal Office of Environment, Forests and Landscape

# Conclusions

Based on preliminary experimental results with 4 measurement- and 2 sampling-methods on 2 Diesel cars with and without particulate trap

- direct sampling from the tailpipe is possible
- sampling from CVS is misleading
- hot/high dilution is possible with rotating diluter
- separation of solid UF and volatile UF is possible
- correlations SPMP/PAS and SMPS/DC are good
- correlations SMPS+PAS+DC/particulate mass not good
- correlations PAS+DC/EC-mass are good
- PAS/DC-ratio supplies chemical “fingerprint” information
- overall accuracy seems good (not enough data yet)
- DL of PAS/DC about 2 % of ambient ( $0,1 \text{ g EC/m}^3$ )
- DL of SMPS about 1 % of ambient / CPC < 0,1 %
- NanoMet follows highly dynamic cycles / free acceleration
- SMPS has no acceptable dynamics / CPC has
- SMPS classifies particle size perfectly / only steady state
- CPC can not classify
- NanoMet-classifier (5 sizes) not tested yet
- calibration methods not tested yet
- more data needed to evaluate repeatability / accuracy
- more data needed to evaluate correlations properly

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very promising results supporting continuation / phase 2

# Application oriented Trap Selection (2)

16

	Type of Trap Regeneration		Exh.Temp. low or uncertain	Engine Emissions	Dynamic or Stationary	Fuel	Lube Oil	Depen- dability	Infra- structure	Commerc. Availability	Application unlimited?
	Diesel Burner	full flow online	+	+	+	+	+	+	+	+	+
		standstill online	+	+	+	+	+	-	-	+	-
	Electric Burner	full flow online	+	+	+	+	+	+	+	-	-
		Standstill onboard	+	+	+	+	+	-	-	+	-
		offboard	+	+	+	+	+	-	-	+	-
	Regeneration	Fuel Additives		-	-	+	+	+	+	+	+
Catalytic Coating		-	+	+	(-)	(-)	+	+	+	-	
NO <sub>2</sub> -Process CRT		-	+	+	-	+	+	+	+	-	
	- Diesel B + Add. - El.B. + Add. + Cat.		+	+	+	+	+	+	+	-	+
			+	+	+	+	+	+	+	-	+
	Engine Heat Release										
	- Fuel Intection - Intake Throtteling	+	+	+	+	+	+	+	+	-	+
			+	+	+	+	+	+	+	-	+